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Steady state spectral model of lasers and its experimental validation for a multi-section DBR laser

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ABSTRACT

In this work, we present a simulation method for estimating the output spectrum of a laser at threshold and we experimentally verify it. The simulation method is based on a T-matrix formulation of the laser mode propagation. The steady state electric field is calculated in the resonator at the lasing threshold and gives the output spectrum of the laser. The validity of this method is experimentally verified by obtaining the spectra of DBR lasers at threshold and comparing them with the calculated spectra.

Keywords: laser, DBR laser, distributed Bragg reflectors, InP, laser model, simulation.

1. INTRODUCTION

Various laser cavity geometries have been proposed and demonstrated in the literature for single mode continuous wave operation, from simple distributed feedback and distributed Bragg reflector (DBR) lasers, to more complex cavities deploying the Vernier effect and super-modes with ring resonators or sampled gratings, V-cavity, asymmetric Mach-Zehnder interferometers and coupled cavities. Each of these configurations bares its own inherent advantages and disadvantages regarding the overall tuning range, continuous tuning over a certain range, stability, linewidth, side mode suppression ratio (SMSR) as well as ease of operation.

Complex cavities however are not straightforward design in order to achieve single mode operation. Many simulation tools, especially time domain solvers, are available to model and design a laser cavities. Such tools are however computationally intensive and therefore time consuming. Therefore we use a steady state simulation method that can quickly calculate the electric field below and at threshold for the wavelength range of interest. This enables us to study and optimize the intra-cavity filter response, the resulting round-trip gain difference between the cavity modes and the subsequent SMSR at threshold as a function of design and control parameters.

In this paper we present the model and demonstrate its validity by characterizing a DBR laser containing two DBR mirrors, a semiconductor optical amplifier (SOA) and an intra-cavity phase modulator. The laser is fabricated in an InP-based generic integration platform [1] and comparing the simulated laser output spectra with experiment.

2. SIMULATION METHOD

The simulation used here is a steady state simulation in which the electric field is calculated inside the laser cavity at the output coupler. The electric field is propagated through the components of the laser cavity with the corresponding phase accumulation and the local propagation loss or gain.

For these simulations, we use a 2x2 T-matrix [2, 3] formulation (Fig. 1(a)), a convention for describing the input and output wave (field) of a two-port circuit. This is a convenient formulation (mathematically equivalent to the S-matrix formulation) which allows us to calculate the total T-matrix of a single pass through all the components in the cavity in a simple way by multiplying their individual T-matrices. The laser cavity includes an SOA, passive waveguide, phase modulator and two DBR gratings. The parameters used describing the SOA and phase modulator are taken from experimental data. The DBRs are described in the laser model as wavelength dependent complex reflectivities. These have been calculated separately also using a T-matrix formulation. The modelling includes a wavelength dependent modal gain, passive losses, phase modulator efficiency and phase modulator voltage dependent losses.

The cavity of the DBR laser is presented in Fig. 1(b). T is the T-matrix of all the intra-cavity components together. The response of the DBR mirrors at both ends is calculated separately as a function of wavelength. For the steady state of the laser a simple linear system of equations with the elements of T, the mirror reflectivities and the amplified spontaneous emission light is set up (Fig. 1(a)). Assuming that there are no reflections inside the cavity other than the mirrors (T-matrix elements $T_{12}$ and $T_{21}$ are equal to zero), we can derive an expression for the value of $A_2$, the electric field strength at the output coupler

$$A_2 = ASE \frac{T_{22}R_{BR}}{T_{11} - R_{FR}T_{22}R_{BR}}$$  

(1)
where $T_{22}$ and $T_{11}$ are the diagonal elements, $R_{BR}$ and $R_{FR}$ are the reflectivities of back and front mirrors respectively and $ASE$ is the amplified spontaneous emission light. Finally, we start off with calculating the laser spectrum for a range of wavelengths at a low gain well below threshold. We then slowly increase the gain until the threshold condition is reached somewhere within the spectrum.

3. DBR LASER THRESHOLD DETERMINATION AND TUNING

The laser chosen here for validation of the model is a multi-section DBR laser which is fabricated in a generic InP-based integration technology by SMART Photonics [4]. The laser includes two uniform DBR mirrors with 50% duty cycle which are 50 and 250 μm long with a pitch of 237 nm, a 370 μm long gain section, a 300 μm long phase section and three electrical isolation sections of 30 μm each, in-between the other four. The phase section is an electro-refractive phase modulator (ERM) which is used in reverse bias operation. The rear DBR grating (250 μm) was also controlled using reverse biasing.

In order to verify the validity of the simulations we have compared the simulated spectra with the experimental spectra obtained close to threshold using a high resolution spectrometer (APEX 2641-B, 20 MHz). Fig. 2(a) presents the output optical power of the laser recorded as a function of the SOA current for a range of voltages in the ERM (0-10 V) and -10 V on the rear DBR mirror. The laser operates single frequency for all current levels presented. In order to identify a lasing threshold more precisely and consistently, we use the second derivative of the optical power versus the SOA current curve which exhibits a distinct maximum at threshold [5]. It should be noted that this threshold definition is a phenomenological one. At these threshold values the gain in the SOA will be very close to its maximum value but still slightly below, as we will demonstrate in the next section. In Fig. 2(b) we can see that a maximum appears which is slightly shifted for different ERM bias voltages indicating an increasing loss in the ERM for increasing reverse bias. The thresholds current levels defined in this way are also consistent with the currents at which the lasing wavelength passes from blue shift due to change in carrier concentration to red shift due to clamped carrier concentration and thermal effects due to SOA current.

The reverse bias ERM voltage tuning was also characterized. In Fig. 3 the recorded lasing wavelength as a function the intra-cavity ERM voltage for different voltages (0 – 10 V) on the rear DBR mirror is depicted. The average slope of the linear fitted curves in the Figure is 10 pm/V and the standard deviation is 0.26 pm/V. The accuracy is limited by the spectrometer resolution used.

![Figure 1. (a) T-matrix definition, (b) A single intra-cavity component (red dashed box) is defined by the multiplication of the individual elements and the laser cavity is formed by the two mirrors.](image)

![Figure 2. (a) The optical power vs. SOA current for different ERM voltages around threshold, (b) the second derivative of the optical power to the current. The current where the maximum lies is defined as the threshold current.](image)

![Figure 3. Wavelength shift as a function ERM reverse bias voltage for different DBR voltages. The average slope is 0.01 nm/V.](image)
4. OUTPUT SPECTRA - MODEL AND EXPERIMENTAL RESULTS

The DBR laser presented above was simulated as described in section 2. In Fig. 4(a) the simulated (red) and recorded (blue) spectra for SOA current 21.2 mA are plotted. The SOA current is the threshold value as defined in section 3. For the measured spectrum, the ERM voltage is -2 V and the rear DBR voltage -10 V. In Fig. 4(b) the measured spectrum (blue) was recorded at 24 mA SOA current (2.8 mA above the threshold) while the DBR and ERM voltages are kept the same. The purple line is the calculated spectrum. For both Fig. 4(a) and (b) the SOA gain is fitted in the model to the measured spectra and it is 46.53 cm⁻¹ and 46.88 cm⁻¹ respectively. This very small change in gain is enough to bring the laser from below threshold to above threshold operation.

There is good agreement between the calculated and measured spectra, particularly in the central part of the spectrum where the lasing mode and the two closest side-modes are located. The resulting SMSR at and above threshold for these conditions are 17 dB and 46 dB respectively. The difference between the two SMSR’s suggests that at 21.2 mA the laser still slightly below threshold where the lasing mode rises rapidly with increasing current. Above threshold however, the changes are much smaller with changing SOA current. For larger offsets from the central peak and the DBR centre, there is an increasing deviation between the two spectra. The extreme calculated cavity modes do not precisely follow the exact wavelength and height of the experimental ones. This is attributed to the DBR model which is used in the calculation which does not describe accurately the fabricated DBR mirrors. The deviation is increasingly pronounced at the edges of the DBR reflection band where the phase is not linear anymore as opposed to the linear phase in the middle of the band. Interestingly, there are larger deviations for shorter wavelengths which can also indicate an asymmetry of the DBR reflection band.

![Simulated and recorded spectra](image)

Figure 4. (a) Simulated (red) and recorded (blue) spectra at threshold for V_{ERM} = -2 V, V_{DBR} = -10 V and SOA current for which the second derivative of the optical power to the SOA current exhibits a maximum (21.2 mA). (b) Simulated (purple) and recorded (blue) above threshold for 24 mA SOA current.

5. CONCLUSION

We present a steady state spectral model of a multi-section DBR laser. The model has been experimentally validated by comparing the output spectra of a multi-section DBR laser at and slightly above threshold with the calculated spectra of our model. These are found in good agreement thus showing that for such a laser cavity the spectrum at threshold can be well predicted. The model can easily be extended to include more components and model complex laser cavities. As an example we have used it to design linear cavity lasers with intra-cavity ring resonators which have also been fabricated. Preliminary characterisation results also indicate the modelling was correct and the devices show single mode operation with very high SMSR.

ACKNOWLEDGEMENTS

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REFERENCES

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